

Analytical Review of the Development of Laser Location Systems

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Abstract

Background/Objectives: The article deals with various laser location systems and schemes of building 3D images used for a distant 3D shooting of objects, automated control movement systems, air and space cartography, object search, finding and tracking of targets for ground, surface and air carriers. **Methods:** Comparative analysis was employed in the research of laser location systems. **Findings:** The authors have presented a review of different schemes of forming 3D images, covering examples of implementations of Laser Location Systems (LLS) with different functions. Characteristics of different LLS were compared and ways of further evolution of LLS in terms of reducing dimensions and increasing performance of the system were proposed. **Applications/Improvements:** This review was conducted to study the possibility of increasing LLS performance by means of hybrid building schemes.

Keywords: 3D Image, Lidar, Laser Location, Scanning Systems

1. Introduction

One of the main ways of getting 3D images of objects in the view field of observation system is a laser location of the space with measuring time of flight of laser radiation to observed objects and back. In this article authors review the developments of various Laser Location Systems (LLS), different schemes of building 3D images with their comparative analysis, and also authors review and compare characteristics of various LLS used for a distant 3D shooting of objects, automated control movement systems, air and space cartography, object search, finding and tracking of targets for ground, surface and air carriers.

2. Schemes of Forming 3D Images

According to the ways of forming 3D images and to the ratio of visual fields of transmitting and receiving systems there are three ways of building LLS are shown in Figure 1¹.

In the system of the first type Figure 1 a probe laser source has narrow directional pattern (small divergence), and optical receiver has wide directional diagram (large field of view). 3D image is formed as a result of consecutive scanning of the subject area by laser beam within the receiver field of view. Receiver records the sequence of pulsed signals at a radiation wavelength which is modulated in intensity in accordance with the spatial distribution of the reflection coefficient. Simultaneously flight time of laser radiation impulses to the reflecting objects and angular coordinates of the laser beam in the receiver field of view are registered.

Size of a resolution element in the system of the first type is determined by angular divergence of the probe laser $2 \cdot \alpha$, and viewing angle is determined by angle of view of the receiving system equal to

$$2 \cdot \beta = 2 \cdot \arctg\left(\frac{\Delta}{2 \cdot F}\right),$$

Where:

Δ – linear size of the receiving photo detector platform,

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F – focus distance of the receiving system.

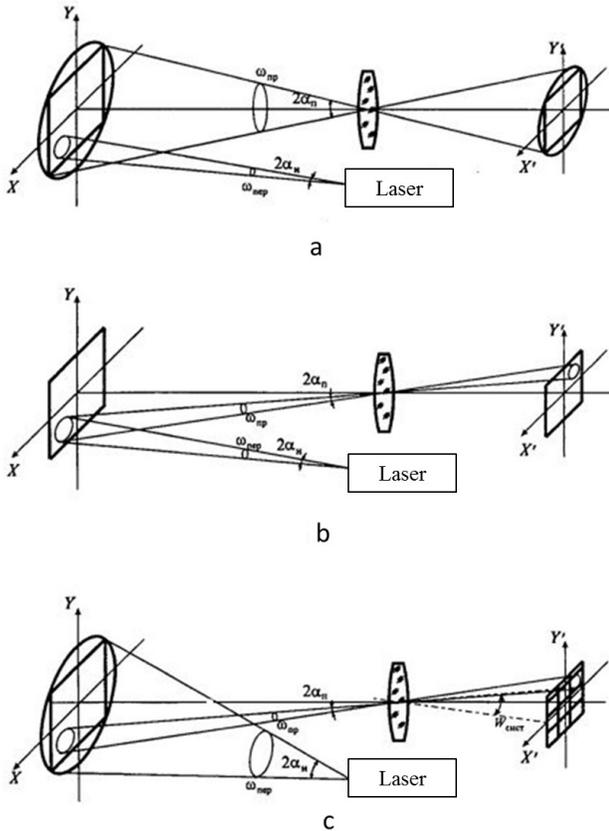


Figure 1. Building options for LLS of 3D images registration.

In the system of the second type Figure 1, both directional diagrams are narrow and are nearly equal in value, besides receiving diagram is scanned in space synchronously with the probe beam. Scanning angle $2 \cdot \Omega$ determines the angular size of the viewing area. The size of a resolution element is determined by angular divergence of the probe laser $2 \cdot \alpha$ which is close to angle of view of the receiving system $2 \cdot \beta$. For the continuous view of the subject area the number of laser impulses in row (column) has to be more than $N = \Omega/\alpha$.

In the system of the third type Figure 1 there is no scanning device, and laser source has a wide directional diagram illuminating the whole field of view. Photo detector in this system is a matrix of photo detectors in the plane of the receiving lens with a total field of view overlapping illumination field. Each of the elements of the receiving matrix (pixel) has a narrow field of view determining angular resolution $\Delta\theta = 2 \cdot \Omega/N$,

where:

N – the matrix dimension.

In literature such system is called Flash Lidar^{2,3}.

Advantages of the system of the first type are simplicity of the scanning system construction and low probability of false object detection which is due to integration of the background brightness variations on the field of view. However the value “signal/noise” in such systems is usually low. That is why systems of the first type are rarely applied in practice.

Systems of the second type⁴⁻⁷, corresponding to the classical LLS of point wise scanning, are characterized by a higher “signal/noise” ratio and weak influence of speckle noise of laser radiation. In two-dimensional scanning of the observed scene by a narrow pulse laser beam the direction of the probe laser beam axis, energy of the laser radiation reflected by the object and flight time of the received impulse relatively to radiation moment are fixed in each impulse. To eliminate the effect of backscatter noise and to filter noises located between the target and a surveillance system, as well as behind the target, a temporary receiver gating is often used by turning it on only for the time corresponding to the time interval in which the emitted laser pulse is in the area of interest for the observer near the object. By the end of the process of single scanning of the space interesting for the observer the processor adds the measurement results and builds a 3D digital image of the objects in the volume of investigation. Resolution element of this image in the plane of objects is the laser spot size determined by its angular divergence and distance. To register a signal in the system of the second type one-element highly sensitive high-speed photo detector placed in the focal plane of the photo detector lens can be used, for example, pin-photodiode. The transverse size of the photo detector must exceed the size of the scattering circle for receiving lens at the operating wavelength, as well as the magnitude of the angular displacement of the beam with respect to scanned sight axis of receiving lens during the flight (in case of long distance and high speed of scanning).

Disadvantages of the systems of the second type are constructive complexity of the synchronous scanning units, limit in impulse frequency due to the flight time to the to the far boundary of the observed zone, and angular misalignment between directional diagrams occurring with reducing the distance to the object in systems with spaced-apart optical axes of the transmitting and receiving channels (bistatic system).

Two types of scanning systems are used:

1. LLS of two-coordinate scanning with linear, spiral, elliptical and other types of deployment. Systems with linear (television) deployment are the most common. The typical examples are laser scanners for architecture and constructional application as well as laser scanners for observing space and providing docking of spacecraft and landing on planets and asteroids;
2. LLS of one-coordinate scanning where displacement of the probe beam in the second coordinate is performed by moving the carrier itself (aviation cartography systems).

Systems of the third type basically allow fixating of 3D image in one laser pulse. However matrix photo detector with matrix dimension $N \times M$ has to provide measurement of the time flight of laser pulse in each pixel, and pulse energy has to be $N \times M$ times higher compared to the system of the second type. Matrix receiver of flash-liar is an integral scheme of $N \times M$ parallel high-speed photo detectors (pixels) sized $5 \dots 100 \mu\text{m}$, and each of them has its own amplifier, measurer of the time intervals and switching keys. Each pixel fixes and records in operative memory energy values of the received laser pulse and its time flight. Resolution element in such system is determined by pixel size (or the scattering circle size for the lens being used, if it exceeds the pixel size), and view filed is determined by the divergence of the probe laser beam coordinated with the field of view of photo detector device. The main technological problem of implementing such systems is the development of matrices of high-speed high-sensitivity photo detectors with a dimension of 128×128 pixels or more, combined with

the scheme of information retrieval, capable of enhancing and commutating at a given frame rate the received signals of nanoseconds containing digital information about the reflected irradiation brightness distribution on the illumination area and distance to targets. Technologies of creating such matrix receivers are developing relatively slow despite the significant financial support.

For space application where there are strict requirements to the weight, size and power consumption of the laser another problem is implementation of illuminating laser with high energy (several J) in the pulse. Hybrid systems are also known which use combination of multi-element photo detector and scanning system⁸⁻¹⁰. In certain situations hybrid systems allow finding acceptable compromise between the conflicting requirements to the system, cost and technological limitations.

Further on in comparative analysis of LLS we will distinguish systems of point wise scanning (second type), flash-lidars and hybrid systems. Point wise scanning systems and hybrid systems will be considered as scanning LLS.

3. Review of the Developments of High-Precision 3D LLS

Existing 3D LLS can be divided according to their purpose. The purpose of the system greatly determines scheme of its building, functioning algorithm and main parameters. The main areas of application of LLS are:

- distant 3D shooting of objects including those inaccessible to other measurement methods;
- systems of automated movement control (for example, car, unmanned aerial vehicle);



Figure 2. Samples of industrial scanners: Trimble GS101, Leica scan-station, Imager 5003, Faro LS880HE.

- air and space cartography;
- space systems for objects search, measurement of trajectory parameters, convergence, landing, optical communication etc.;
- systems for search, detection and tracking of targets for ground, surface and air carriers, including active homing agents.

3.1 LLS for Distant 3D Object Shooting

A wide range of scanners forming 3D images of geological, industrial, artistic and other objects are currently manufactured. Examples of these scanners are presented in Figure 2 and their parameters are listed in Table 1.

Measurement of the flight time of laser pulse or measurement of the phase difference of the emitted and the reflected modulated laser signal are used to determine the distance. There are devices which measure large distances using pulse method and small distances using phase method^{11,12}. Nearly all scanners of this class use azimuthal scanning of the transceiver channel about a vertical axis in combination with the vertical scan using a scanning mirror. Torque or stepper motors are used for azimuthal scan, and electromechanical drives or galvanic mirrors are used for vertical scan. As shown in Table 1, working distances of this class LLS do not exceed 100 m and for probing they use relatively cheap and energetically efficient semiconductor lasers with an eye-safe power level and / or wavelength. Laser pulse frequency does not exceed 5 kHz, pulse length does not exceed 5–10 ns and scanning time for the whole view field is tens of minutes. Angular resolution of these scans is 0.001°–0.02°, accuracy of measuring the height of the surface relief is 3–6 km.

In this class of LLS a subclass can be identified. This subclass aims to shoot surface relief of roads and railways

where one-coordinate scanning is a scanner rotation, and scan of the second coordinate is carried out by the movement of the transport carrier. Coordinate binding is secured by carrier satellite navigation system, scanner rotation angle sensor and a speedometer. General view and measurement results using such system are presented in Figure 3 and Figure 4.

3.2 Systems of Vehicle Automated Movement Control

In robotic systems which are transport platforms moving on the surface of the Earth or space object LLS of circular azimuth view can be used where laser and receiving system rotate round the building axis of the device oriented vertically or angularly to the vertical. Second coordinate scanning can be implemented by means of a rotating mirror prism or oscillating mirror on galvanic drive. In mentioned above systems for industrial scanning real time information update is required to control the vehicle. Therefore speed characteristics of the scanning device and laser pulse frequency requirements are close to the limit for known devices. That is why a hybrid building scheme is used in known LLS with parameters acceptable for practice.

The winner of the automobile-robots race 2005 DARPA Grand Challenge and the following races was the car equipped with high-resolution lidar HDL-64E S2 (Velodyne, USA) Figure 5 and Figure 6. This is the lidar with horizontal view field of 360° and vertical view field of 26.8°. Frame frequency of LLS is regulated in the range of 5–15 Hz. Viewing area of LLS is up to 180 m and measurement accuracy is 2 cm. Ethernet interfaces 100 Mb/s is used for data transmission.

Table 1. Parameters of the scanning system motor

Manufacturer/Model		Trimble GS101	Leika SDS3000	IMAGER 5003	Faro LS 880HE
Measurement method		Time-of-flight		Phase	
View field, degrees		360×60	360×270	360×210	360×320
Distance, m		2-100	1-100	1-53.5	78
Scanner speed, points/s		Up to 5000	Up to 4000	500000	120000
Angular dimension, degrees	Vertically	0.0017	0.0034	0.018	0.009
	Horizontally	0.0017	0.0034	0.01	0.00076
Scanner accuracy, mm		6	4	6	3/10
Control		Notebook	Notebook	Notebook	Notebook
Presence of a TV camera		analogue	digital	option	option

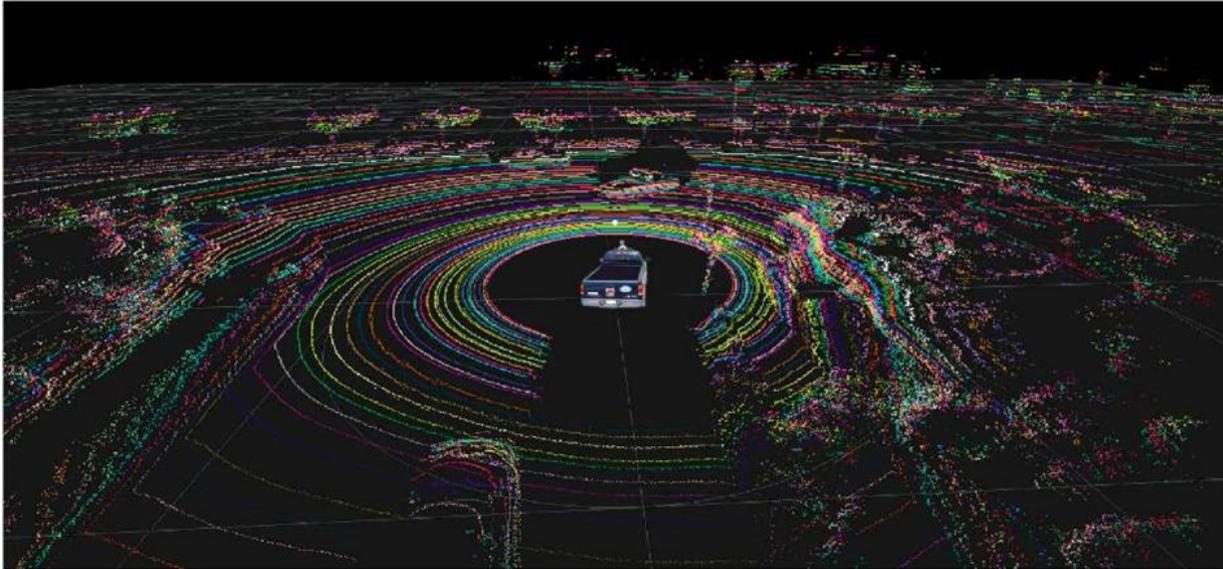


Figure 3. Riegle-VMX-250 scanner on a car.

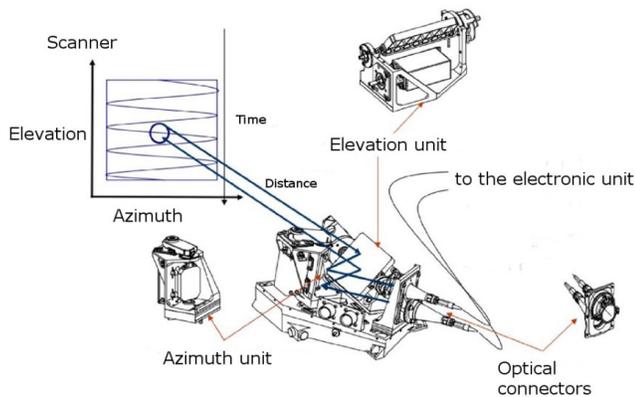


Figure 4. The result of computer processing of scan data by Riegle VZ 400 a scanner.

For implementation of such high parameters the developers used following technical solutions. System of 16 diode lasers (1 class safety) with wavelength of 905 nm mounted on a single board, and each of them placed at a predetermined angle to the surface of the board was used for instant illumination of space zone sized $14^\circ \times 14^\circ$ approximately. Four such adjusted boards are used to illuminate area of $27^\circ \times 27^\circ$.

To register reflected laser pulses two lenses with view fields overlapping laser diodes illumination area and two matrices of photodiodes sized 8×4 were used.

Therefore in HDL-64E S2 hybrid scanning scheme was implemented where information capacity of 1.8 million points per second is achieved at relatively small lidar head rotational speed.

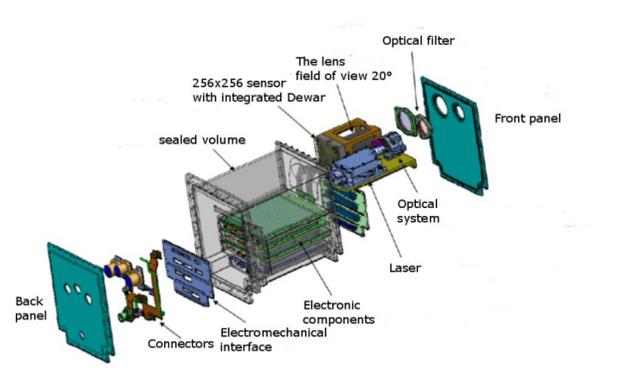


Figure 5. General appearance of HDL-64E S2 scanner.

3.3 Space Systems of Laser Location

Flight tests of various LLS have been performed since 1990 on various space shuttles using retro reflectors on passive spacecraft. Researchers also performed rendezvous and docking with the orbital stations “Mir” and “International Space Station” or in automated spacecraft. The results of these tests proved reliability and potential of LLS application¹³⁻²⁰. The largest amount of studies was performed with (TGM) Tele Gonio Meters (another name Rendezvous and Docking Sensor (RVS)²¹ developed by Jena-Optronic (Germany). TGM passed flight tests on “Space Shuttle” spacecraft (1997), ATV spacecraft (Autonomous Transfer Vehicle, 2008 of the European Space Agency) and HTV spacecraft (H-II Transfer Vehicle, 2009 of the Japan Aerospace Exploration Agency).

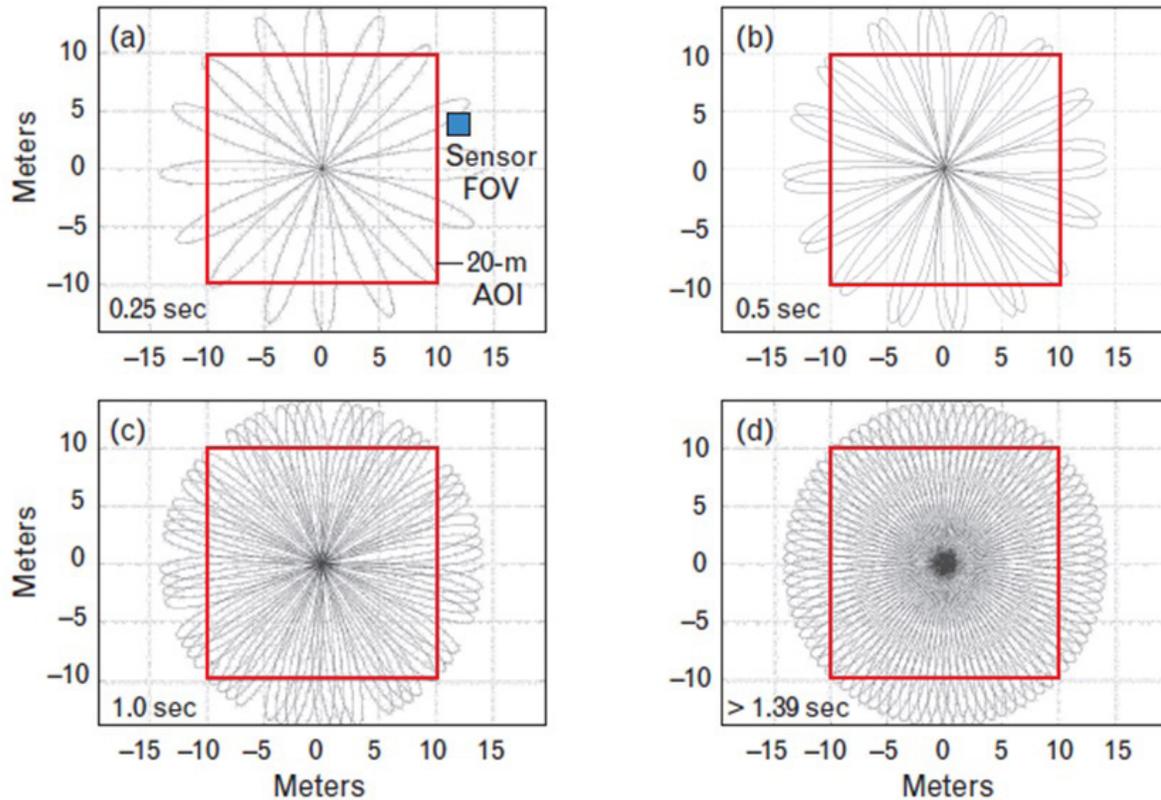


Figure 6. Image maid from the cloud of points by HDL-64E S2 scanner showing the situation when the car-carrier (in the center) observes another car.

Optic equipment of docking parameters measurements was used in docking of ATV spacecraft with International Space Station from distance of 259 m. This optic equipment contained two VDM video meters (a video camera based on star sensors) and two laser TGM (main and reserved). Docking control was performed based on the data from VDM, and TGM worked as a control channel.

MDA Optech (Canada) developed RLS (Rendezvous Lidar Sensor) system aimed to inspect and service a spacecraft in space, to preserving from clashing, and to perform Rendezvous and Docking operations²². The system uses mechanical scanning with a mobile mirror and time-of-flight measurement method. RLS passed flight tests at XSS-11 automated spaceship. Range of measurements for diffusely scattering objects (without reciprocal optical devices) is up to 3 km with an error of less than 1 cm.

Neptec (Canada) has developed TriDAR system for the same purposes. The system passed flight tests at Space Shuttle spaceship in 2009-2010²³. A combination of two

measurement methods was implemented in TriDAR system: time-of-flight measurement method at large distances and triangulation method for near field. The measurements are provided in a range from 5 m to 2 km.

For obtaining 3D images in the mentioned systems LLS of the second type is used where a narrow laser beam moves in synchronism with the narrow receiver view field by means of optical-mechanical scanning system.

Building principle for two-coordinate scanning system is the following. The system has transmitting channel on the basis of pulsed fiber laser and a receiving channel with a photo detector on the basis of avalanche photodiode. The laser beam and view field of the receiving system are scanned synchronously with a system of two mirrors with electromechanical drive. Parameters of three options of implementing the system are listed in Table 2. Line scanning speed is 400°/s. The divergence of laser beam is 2.5 mrad i.e. number of resolution elements is 280×280, scanning time for the whole view field of 40°C is about 28 s.

A layout of the lidar measurement system was developed and tested in the Central Research Institute of

Table 2. Parameters of three options of implementing RVS system

Parameter	RVS	RVS 3000	RVS 3000 3D
Scanner parameters			
View field	40°×40°....1°×1°	40°×40°....1°×1°	40°×40°....1°×1°
Measurement accuracy	<0.06°	<0.05°	<0.05°
Laser			
Wavelength	910 nm	1.5 μm	1.5 μm
Operation range for co-operative space object			
Minimum	<1 m	<1 m	<1 m
Maximum	>1500 m	>1500 m	>1500 m
Operation range for non-co-operative space object			
Minimum	-	<1 m	<1 m
Maximum	-	>100 m	>1000 m
Power consumption			
Minimum	40 W	30 W	35 W
Medium	70 W	50 W	60 W
Physical specifications			
Weight of the optical part	5.9 kg	14.6 kg	8.0 kg
Weight of the electronic part	7.7 kg		
Cables	1.0 kg		
Sizes of the optical part, mm	265×345×195	286×310×195	286×310×195
Sizes of the electronic part, mm	315×224×176		
Electrical interface			
Power	27.0 V ± 1.5 V		
Data transfer	MIL-1553B	MIL-1553B, Space Wire	
Output data	azimuth, angle of elevation, range	azimuth, angle of elevation, range	azimuth, angle of elevation, range, cloud of spots of a 3D image of an object

Robotics and Technical Cybernetics as the on-board LLS for a new spaceship (Rocket and Space Corporation “ENERGIA” after S.P. Korolev)²⁴. This system detects a passive spacecraft at distance of 30 and 10 km respectively depending on the presence or absence of a corner reflectors system on the object. In a search mode the view field if 40°×40°, and viewing time does not exceed 20 s. The rate of coordinate information refresh is 5 Hz for objects at medium and short distances when an object can be detected and a scan area is reduced. Weight of the device is 15 kg, power consumption in the active phase is 100 W or less.

It can be seen from the review of the space LLS that those with electromechanical two-coordinate scanning are currently the main means of obtaining 3D images of the environment in space applications. Lately devel-

opers’ attention has been drawn to 3D flash-lidars. It is clear that application of a flash-lidar that does not use optical-mechanical scanning is highly attractive for space systems. Based on 3D flash-lidar “Advanced Scientific Concepts Inc.” Company developed rendezvous and docking system called KA Dragon which was tested in 2009 at the “Space Shuttle” spacecraft.⁸ LLS called “Dragon Eye” is aimed to inspect and detect spacecraft damages. Promotional materials say that measured distance range is from 1 m to 4 km (the latter is in case of a cooperative object with retro reflectors) with minimum error of 5 cm. Frame frequency is up to 30 Hz with a matrix receiver dimension 128×128.

In July 2010 Vision Navigation Sensor (VNS) system²⁵ developed in NASA Research center in Langley passed the flight tests. Measurements in the system are performed by

retro reflectors placed on a passive spacecraft with maximal operating distance being 5 km¹³.

3.4 LLS for Search, Detection and Tracking of the Moving Objects

The main requirements to LLS of this class are a long operating distance (more than 5 km), unobscured view field (from $1^\circ \times 1^\circ$ to $45^\circ \times 45^\circ$) and high rate of data refreshment required for tracking of the moving objects (more than 10 frames per second).

Several LLS for search and tracking of the moving objects built according to the classical scheme of point wise scanning have been developing since 1980th till nowadays. However combination of the parameters required for effective functioning was achieved in a limited number of systems. Therefore it can be noted that LLS with scanning are applied much more rarely compared to television and thermo vision passive observation systems added with rangefinder measuring the distance to the object in the center of the view field of the surveillance system.

Probably evolution of the technologies of the laser sources development and multi-element high-speed photo detectors with per-pixel measurement of the time of flight could change the current situation. 3D Imaging Laser Radar System "Jigsaw" (Lincoln Laboratory, USA) can be an example of a new-generation LLS. Technical characteristics of these LLS are listed in Table 3.

This system should be considered as a hybrid LLS because it uses scanning of the view field of matrix of photo detectors with a dimension of 32×32 with per-pixel time of flight measurement. The features of the system are Risley scanner (two counter-rotating wedges placed in front of the lens of the receiving channel) and chamomile-like scanning trajectories due to the rotating speed differences.

Central Research Institute of the Robotics and Technical Cybernetics is working on the study of the possibility to increase performance of LLS by using hybrid building schemes. The model of LLS with one-dimension scanning and a linear photodetector²⁶ is being developed. In this scheme a probe beam is formed with significantly differing angular divergence along the coordinates, and which is scanned in the space around the axis parallel to the coordinate with higher divergence. A line of receiving platforms is placed in the image plane of the receiving lens, and it is also parallel to the rotation axis of the scan-

ning mirror. A line of the receiving platforms is formed by N ends of optic fibers distributing received echo signals at the N separate photo detectors. The scheme allows significant simplification of the scanning system and avoiding of matrix photo detector which is technically challenging.

Table 3. Jigsaw system parameters

Parameter	Value	Note
Nominal range	150 m	
Scanning field	10.8°	diameter 28.3 m if distance is 150 m
Operating wavelength	532 nm	
Field in a far area	32×32	Agreed with the receivers
Duration of the laser pulse	300 ps	
Pulse repetition rate	16 kHz	
Diameter of the receiving aperture	7.5 cm	
Effective focus	300 mm	
Aperture ratio	$f/4.0$	
Number of receivers	32×32	
Size of receivers	100 μm	
Total view field	$10.1 \text{ mrad} \times 10.1 \text{ mrad}$	
Range resolution	40 cm	Goal – 7.5 cm

4. Conclusions

According to the analytical review performed by the authors, it can be concluded that LLS remain the main way of obtaining 3D images of the surroundings. Evolution of the technology of matrix time-of-flight matrix sensors development has led to the studies of fundamentally new location systems called flash-lidars. The main advantages of this system are the absence of the scanning system and high speed of obtaining information about the surroundings. The disadvantages of the flash-lidars are technological complexity and high cost of the matrix photo detectors used, as well as the need of using probe lasers with energy of tens of joules which have high weight, sizes and energy consumption. New hybrid LLS using combination of a scanning system and multi-element photo detector are of great practical inter-

est. Hybrid LLS can provide operating range, weight and sizes close to those for point wise scanning systems but with higher speed of obtaining information. Hybrid LLS could be an optimal choice for solving the problems of building 3D images of high resolution in a short period of time at long distances with low physical specifications of the laser locator.

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